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ABSTRACT.
RF-induced pinch of ^{3}He minority ions has been observed in JET affecting the γ-emission, the Alfvén eigenmode excitation, the diamagnetic energy and the sawtooth period. The tomographic reconstruction of the γ-emissivity profiles are consistent with RF-induced detrapping. The experimental results have been compared with simulations with SELFO.

1. INTRODUCTION

During intense ICRH energetic anisotropic tails on the distribution functions of the resonant ions are produced [1]. The toroidal acceleration due to absorption of toroidal angular momen-tum from the wave displaces the turning points of the trapped ions vertically [2]. Particles interacting with waves propagating anti-parallel and parallel to the plasma current will experi-ence an outward and an inward drift respectively; the RF-induced pinch. Ultimately the poloidal turning points will meet in the midplane and the orbit becomes detrapped [3]. At high energies a majority of the detrapped ions will follow co-current passing orbits [4]. If these ions are heated further they will not continue to pinch, but will be shifted to the low field side (LFS) by the increasing r B and curvature drifts.

The RF-induced transport can be studied experimentally by altering the toroidal mode spec-trum of the ICRH antennae. In JET two antenna phasings with high directivity are used, with +90° and −90° phase difference between the antenna straps, exciting spectra dominated by waves traveling parallel and anti-parallel to the plasma current, respectively.

The presence of an RF-induced pinch of hydrogen minority ions has previously been observed through the effect on sawtoothing, line integrated proton distribution function and triggering of Alfvén eigenmodes [5]. Further, a hot spot of energetic ^{3}He ions on the LFS during ICRH with a symmetric toroidal wave spectrum, was observed through tomographic reconstruction of -emission [6]. The latter observation is found to be consistent with the RF-induced detrapping into co-current passing orbits that are strongly shifted to the LFS [7, 8].

2. EXPERIMENTAL RESULTS

An overview of two JET pulses heated by 6:8MW of ICRH with +90° and −90° phasing is shown in Fig. 1. The magnetic field 3:4T and the ICRH frequency 37:3 MHz are chosen to heat the 1-2 % concentration of ^{3}He, in a ^{4}He plasma, at $R_{res} \approx 2.8$m. In the pulses 54239 and 54243 with +90° and −90° phasing, respectively, the density and ICRH power are the same up to 10s, while clear differences in the γ emission, the AE activity, the diamagnetic energy and the sawtooth behaviour, are observed (see also [9, 10]. The γ-ray emission from $^{12}C(^3He, p\gamma)^{14}N$ reactions has been measured along 19 lines of sight spanning a mesh over the poloidal cross section [11]. The emissivity profiles have then been tomographically reconstructed, Fig. 2 [12]. From the emissivity profiles it is evident that the number of particles with a significant reaction rate is larger with +90° phasing. Also the shape of the emission profiles are different; with −90° phasing the emission comes mainly from the cyclotron resonance layer, which is consistent with a population of trapped ions with turning points at the resonance. The emissivity with +90° phasing comes mainly from the LFS of the resonance layer, requiring large Doppler shifts for these ions to be resonant. Since most of the power in the +90° phasing is in wave modes propagating parallel to the plasma current, the Doppler shifted resonance of counter-current passing ions is on the high field side (HFS) of the resonance layer, and consequently the observed emission comes from trapped and co-current passing ions.

An error analysis of the tomographic reconstruction has been done by varying both the input from the measurements within the experimental error bars and the reconstruction parameters [12]. The analysis shows that the characteristic properties of the profiles are very rigid.

Fast ions are known to affect the stability of MHD modes [13], allowing indirect measurements of the difference between the tails with +90° and -90° phasing. In pulse No: 54239 (+90°) the sawtooth period is a factor ~ 1:8 times longer than in pulse No: 54243 (-90°) [9]. This is consistent with a higher fast ion energy content inside the q = 1 surface with +90° phasing, which is stabilizing the internal kink mode [14]. By comparing the thermal and the diamagnetic energy, the fast ion energy content within the whole plasma is shown to be larger with +90°0 phasing. Alfvén eigenmodes (AE) can be destabilized if the pressure gradient of the resonant energetic ions is sufficiently large. In Pulse No: 54239 both toroidal and elliptical AEs are observed by an array of Mirnov coils [15], see Fig. 1. With the opposite phasing, in pulse No: 54243 (-90°), the spectrogram shows no excitation of these modes, indicating a smaller pressure gradient of resonant energetic ions, and/or smaller effective tail temperature than with +90° phasing.

Pulse No: 54081 D(^{3}He) was heated by NBI and ICRH with $R_{res} \approx$ 2:8 and +90° phasing. It had a reversed shear and an internal transport barrier, but the measured profile was similar to Pulse No: 54239 (+90°) [9]. Further, Pulse No:54240 (-90°) was prepared in the same way as Pulse No: 54243 (-90°) and have a similar profile, showing the reproducibility of the experimental results.

3. ANALYSIS AND SELFO SIMULATIONS

The two Pulse Nos: 54239 (+90°) and 54243 (-90°) have been analyzed using the SELFO code [7, 16], which calculates the distribution function of resonant ions, using the FIDO code [17], and the magnetosonic wave field, using the LION code [18]. The two codes are self-consistently coupled by using the dielectric tensor, calculated from the distribution function obtained with FIDO, when calculating the wave field.

With the +90° the inward pinch confines the fast ions to the central plasma, where the RF wave field is strong, whereas for with -90° these ions drift outwards. An ion heated with +90° phasing will therefore spend a longer time in resonance with the wave, reach higher energies and collide less with the ions. Consequently the slowing down time is longer and the fast ions energy content higher. By comparing the diamagnetic and thermal energy the perpendicular energy content of the fast ions is found to be of the same order as calculated with SELFO; 0:5 = 0:46MJ (measured/ SELFO) with +90° phasing and 0:3 = 0:35MJ (measured/SELFO) with -90° phasing.

When ions excite AEs they exchange energy and angular momentum with the wave. For AEs propagating parallel to the plasma current, as in pulse No: 54239, the ions would be displaced outwards when they loose energy, analogous to the RF-induced pinch. Thereby increasing the collision frequency and consequently decreasing the fast ion energy content. In spite of the AE activity the fast ion energy content is higher in Pulse No:54239 (+90°).

In the simulations the pressure of ions with energy above 600keV are shown in Fig. 3, which can be compared with the γ-ray emissivity profiles in Fig. 2. In pulse No: 54243 (-90°) most of the ions are trapped with their turning points on the cyclotron resonance layer. Since the trapped ions spend most of their time at the turning points the emissivity profile is spread out along the resonance layer. However, the vertical spread is limited by focusing of the wave field.

In pulse No: 54239 (+90°) many ions are confined to the LFS of the resonance layer, requir-ing a Doppler shift to be resonant with the RF-wave. Such ions are naturally produced by the RF-induced detrapping into co-current passing orbits with the +90° phasing. Without the detrapping the pressure and -emissivity profiles with +90° phasing would look similar to those with -90°, only differing in the magnitude and the spread along the resonance layer.

CONCLUSIONS

The RF-induced transport can be deduced from the differences between pulses with +90° and -90° antenna phasing. The measured diamagnetic energy, sawtooth period and the excitation of EAE and TAE modes, all indicates that the fast ion energy content is higher with +90°, than -90° phasing. This is consistent with the RF-induced pinch. The part of the ^{3}He tail that have a finite cross section for $^{12}C(^{3}He,p\gamma)^{14}N$ reactions were directly observed in the -emission from this reaction. The observation show a larger population of such ions with +90° phasing; consistent with an RF-induced pinch. This population is mainly located on the LFS of the cyclotron resonance layer; consistent with an RF-induced detrapping. Simulations with the SELFO code reproduces the measured perpendicular fast ion energy content, and produces pressure profiles similar to measured γ-emissivity profiles.

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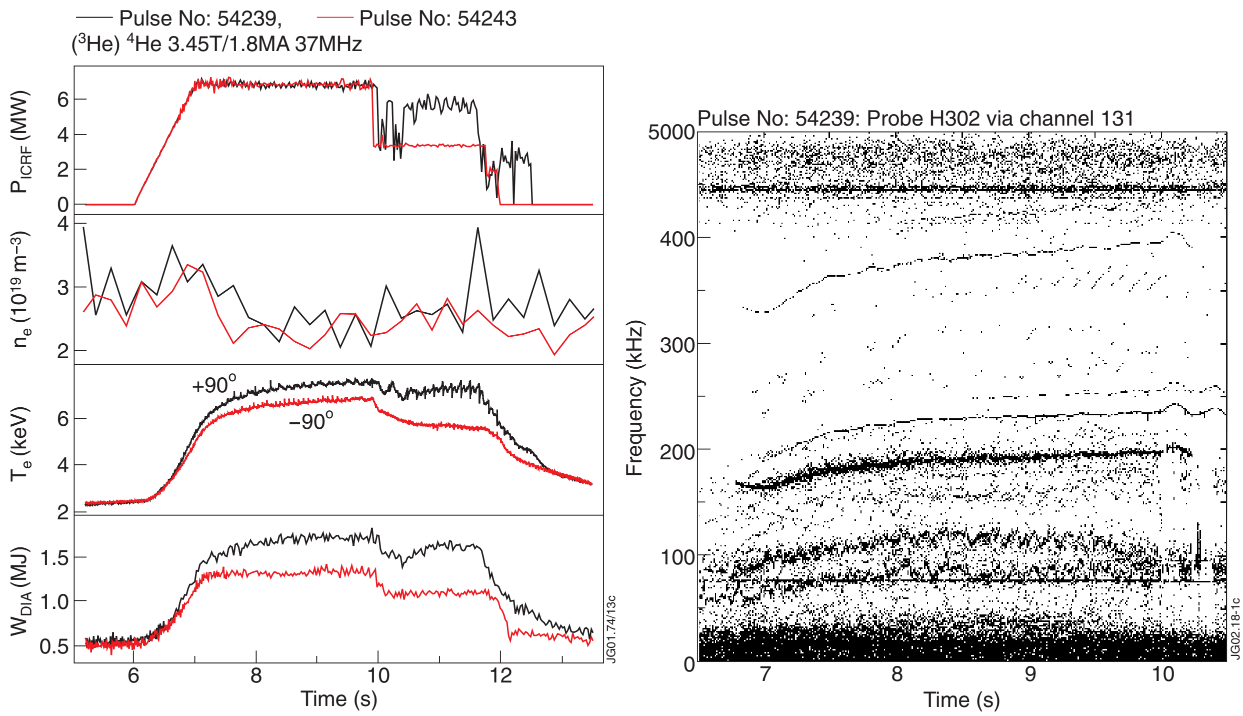

Figure 1: To the left, experimental parameters from JET pulse Nos: 54243 and 54239. To the right, spectrogram of the MHD activity, TAEs at 150-250kHz and EAEs at 325-450kHz are clearly seen.

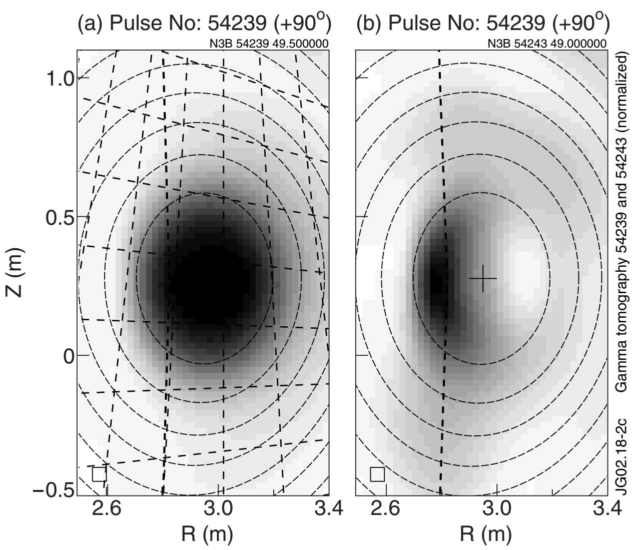

Figure 2: Tomographically reconstructed profiles of the γ-ray emissivity from $^{12}C(^{3}He,p\gamma)^{14}N$ reactions in the poloidal cross section. The maximum emissivities in Pulse No: 54239 and Pulse No: 54243 are 2 and 1 [$x10^{15}$ photons $m^{-3}s^{-1}$], respectively. The lines of sight are drawn with long-dashed lines, the flux surfaces from EFIT with dashed lines, and the resonance layer with a dotted line resonance of ^{3}He.

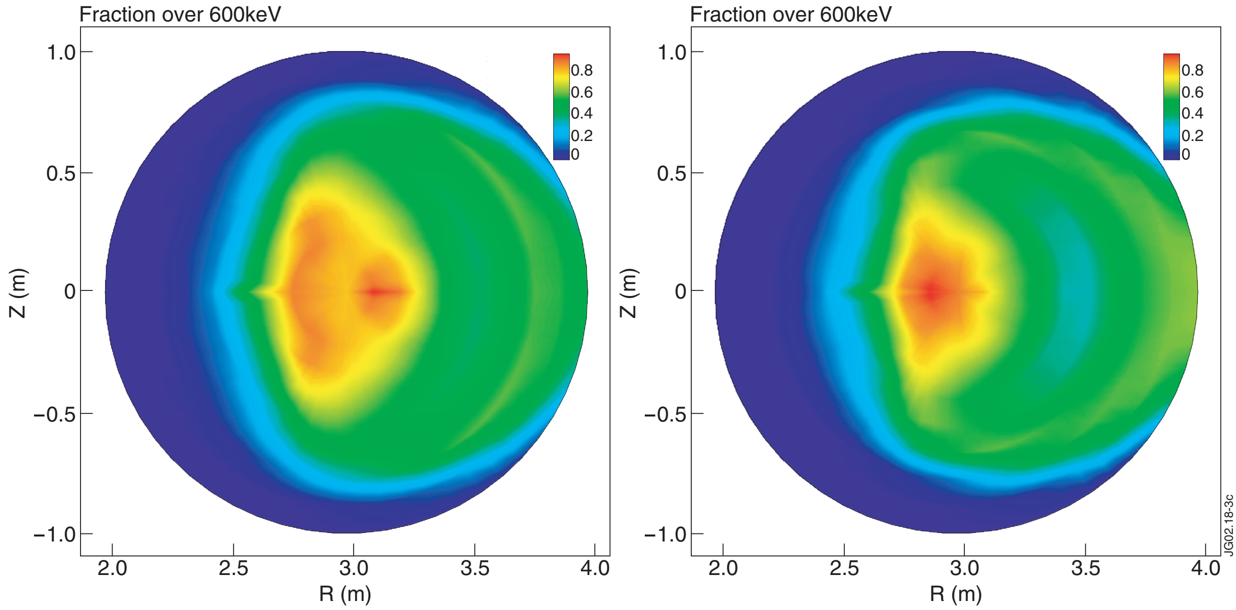

Figure 3: Pressure in the poloidal cross section of ions with energy above 600keV. To the left, pulse No: 54239 (+90°) and to the right Pulse No: 54243 (-90°).